Ciencia & Futuro V. 16. 2026 ISSN: 2306-823X

Received: 12/3/2026/ Accepted:28/4/2026

Evaluation of Energy Efficiency in the Ponds of the Guajaca Frank País Shrimp Farm, Cuba

Evaluación de la eficiencia energética en los estanques de la camaronera Guajaca Frank País, Cuba

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Abstract: The purpose of this research is to evaluate the energy efficiency of the electrical systems in the ponds of the Guajaca Frank País Shrimp Farm in Cuba. The analysis focuses on three shrimp farm services (1, 2, and 4) that supply energy to the ponds, where high-energy consumption, energy transformation losses, and a low power factor were evidenced. These shortcomings lead to financial penalties that are laid down by the power company. Through an electrical diagnostic, which includes measurements of electrical parameters and billing analysis, the installation of capacitor banks is proposed to correct the power factor and reduce energy losses. The results show that reactive power compensation can significantly improve energy efficiency, reduce financial penalties, and contribute to environmental sustainability by decreasing CO_2 emissions. This paper provides a replicable framework for improving energy efficiency in similar industrial environments.

How to cite: Blanco-Cuba, L., Rodríguez-Durán, V.G., Robles-Laurencio, O., Zúñiga-Ortíz, L., Jardínez-Correa, G. (2026). Evaluation of Energy Efficiency in the Ponds of the Guajaca Frank País Shrimp Farm, Cuba, Cuba. *Ciencia & Futuro*, *16.*
https://revista.ismm.edu.cu/index.php/revistacyf/article/view/2954

Keywords: electric charge, power consumption, electrical power distribution, industrial management

Resumen: El propósito de esta investigación es evaluar la eficiencia energética de los sistemas eléctricos en los estanques de la Camaronera Guajaca Frank País, Cuba. El análisis se centra en los servicios (1, 2 y 4) que suministran energía a los estanques, donde se identificaron altos consumos, pérdidas por transformación de energía y bajo factor de potencia. Estas ineficiencias provocan penalizaciones económicas impuestas por la empresa eléctrica. A través de un diagnóstico eléctrico, que incluyó mediciones de parámetros eléctricos y análisis de facturación, se propone la instalación de bancos de capacitores para corregir el factor de potencia y reducir las pérdidas de energía. Los resultados demuestran que la compensación de la potencia reactiva puede mejorar significativamente la eficiencia energética, reducir las penalizaciones económicas y contribuir a la sostenibilidad ambiental al disminuir las emisiones de CO_2. Este estudio proporciona un marco replicable para mejorar la eficiencia energética en entornos industriales similares.

Palabras clave: carga eléctrica, consumo de energía, distribución de energía eléctrica, gestión industrial

1. Introduction

Energy efficiency refers to the optimization of energy use in activities and electrical devices with the aim of reducing energy consumption and minimizing environmental impact (Gómez, 2016; Vega *et al*., 2024; Mondragón *et al*., 2025). The global demand for energy efficiency in industrial processes has increased due to the rising of energy costs and environmental concerns (García and Aguado, 2019; Solis-Mora & Gruezo-Valencia, 2022; Valencia-Bautista *et al.,* 2022; Cárdenas-Monné & Baños-Martínez,

In the industries, the low power factor, the deterioration of the electrical grid, the use of nonlinear loads, underloaded transformers, and overheating reduce energy efficiency (Freire *et al.,* 2019; Gómez, 2021; Ávila & Segarra, 2022; Maldonado, 2025). To minimize these impacts, it is necessary to understand how they are generated and the methods for correcting them.

In Cuba, the shrimp farming industry is a big electric power, making it essential to optimize power use to reduce operating costs and the environmental impact. This paper is conducted at the Guajaca Frank País Shrimp Farm, where inefficiencies in the electrical systems of the shrimp ponds have led to high energy consumption (18%), significant energy losses, and a low power factor, resulting in financial penalties.

The electrical diagnostics are essential for identifying inefficiencies in the electrical systems, such as high energy losses, unbalanced loads, and low power factor (García & Aguado, 2019; García & Hernández, 2021; Martínez & Gassinski, 2022; Collins & Tomalá, 2025). In the diagnostic process a series of factors is defined, that allow to know the characteristic parameters of each load and the electrical system (García & Aguado, 2019), as well as quantitatively expressing their variations, their effects on the system, and the relationship between loads (Rueda, 2023). This paper presents a preliminary, first-level diagnostic, which includes visual inspections, electrical parameter measurements, and billing analysis.

The main objective of this paper is to evaluate the energy efficiency of the electrical systems in the ponds of the Guajaca Frank País shrimp farm and to propose corrective actions to improve the power factor and reduce the energy losses. The research highlights the importance of reactive power compensation using capacitor banks as a cost-effective solution to improve energy efficiency and reducing the operating costs (Pérez *et al.,* 2022).

2. Materials and methods

The investigation was carried out in the pond area of the Guajaca Frank País shrimp farm. Services 1, 2, 3, and 4 are distributed through the pond modules, where the shrimps are raised, next to the salt water pumping station, which experiences the greatest impact from penalties due to the low power factor.

2.1. Power factor and reactive power compensation

The power factor is a critical parameter in the electrical systems. It represents the ratio between active power and apparent power. A low power factor indicates high reactive power consumption, which increases the energy losses and reduces the capacity of the electrical equipment (Diaconescu *et al*., 2025). Reactive power compensation using capacitor banks is a widely used method to improve power factor and reduce the power losses (Majidzadeh *et al.,* 2025; Lujano-Rojas *et al.,* 2026).

Most of the industrial loads are inductive in nature (Pérez, 2016; Giha-Yidi, 2023; Ramos *et al.,* 2024). The inductive loads result in a low power factor, with the associated problems. The power factor is the ratio between the active power (which performs work on the load) and the apparent power of the circuit (equation 1):

$$cos\varpi = fp = \frac{P}{S} = \frac{P}{\sqrt{3}VI} = \frac{P}{\sqrt{P^2 + Q^2}} = co\,s\left(tan^{-1}\left(\frac{Q}{P}\right)\right) \qquad [1]$$

Where:
P: Active power (kW)
S: Apparent power (kVA)
Q: Reactive power (kVAr)
Fp: Power factor
Φ: Phase angle

Operating an electrical installation with a low power factor, in addition to the impact on the power billing, has other implications, particularly regarding the capacity of electrical power transformation and distribution equipment and the efficient use of machinery and appliances (Silva *et al*., 2018). The apparent power and load current (I) depend inversely on the power factor of the load:

$$S = \frac{P}{cos\varphi} \quad (\mathrm{VA}) \qquad [2]$$

$$I = \frac{P}{\sqrt{3}Vcos\varphi} \quad (\mathrm{A}) \qquad [3]$$

2.2 Power Factor Correction Methods

Improving the power factor in the industry is only achieved through the correct combination of different methods for raising it, each of which must be technically and economically supported (Ali *et al*., 2023). The power factor correction methods can be considered within the following general groups:

a) Reduction of reactive power consumption without the application of compensating means.

b) With the application of compensating means.

The power factor correction through the installation of a capacitor bank can be carried out in three main ways, depending on the load characteristics, location, and the appropriate means for future maintenance:

1. Individual or Fixed Compensation: This method is used in equipment with continuous operating cycles and significant reactive power consumption, primarily electric motors and transformers. The capacitor is installed at each one of the loads, so that the only conductors affected by reactive power, are those ones connecting the load to the capacitor. The advantage of this configuration lies in the fact that the reactive power is confined between the capacitor and the load, leaving the remaining lines free of reactive power.

2. Group Compensation: This is recommended when a group of loads, whether identical or different, are connected simultaneously and demand a constant amount of reactive power. The group configuration allows that the capacitor banks may be installed at the motor control center (MCC), used only when the loads are operating and the reactive power of the electrical power distribution lines are removed and when the facility economic investment is reduced.

3. Centralized or Main Compensation: The total power of the capacitor bank is installed at the electrical connection, near the power distribution panels. The total power of the capacitor bank is divided into several blocks or stages, connected by an automatic regulator that connects or disconnects them as needed, according to the instantaneous reactive power consumption (Chicaiza Díaz & Arcos, 2015). Centralized compensation allows for greater utilization of the capacitor capacity, better voltage regulation in the electrical system, and adjustment of the capacitor bank's power according to the requirements at any given time (Figure 1).

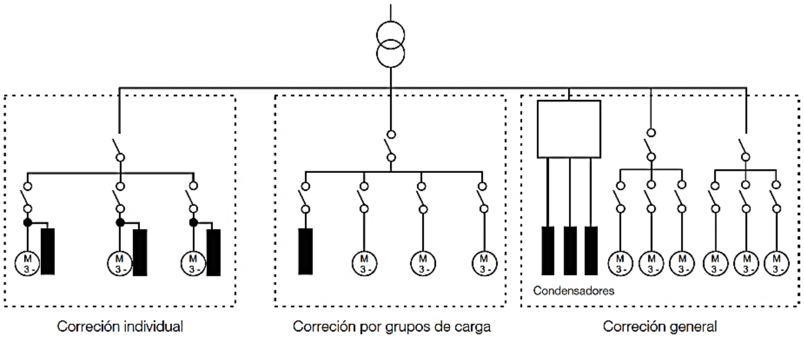

Figure 1. Capacitor Banks methods (Chicaiza Díaz & Arcos, 2015).

2.3. Electrical parameter measurements

The following electrical parameters were measured: current, voltage, active power, reactive power, power factor, and energy consumption, in services 1, 2, and 4 of the shrimp ponds. A network analyzer and a multimeter ere used.

2.3.1. General behavior of the electrical magnitudes

The induction motors coupled by mechanical drives to the rotating vanes, (aerators) are the main loads to be considered, when analyzing the electrical variables and magnitudes that influence on the low power factor, for which these services are penalized. The voltages measured on a typical panel for connecting these motors, indicate high line voltage values, that increases to some extent, the reactive power consumption of the network; which at the same time, influence on the power factor (Figure 2).

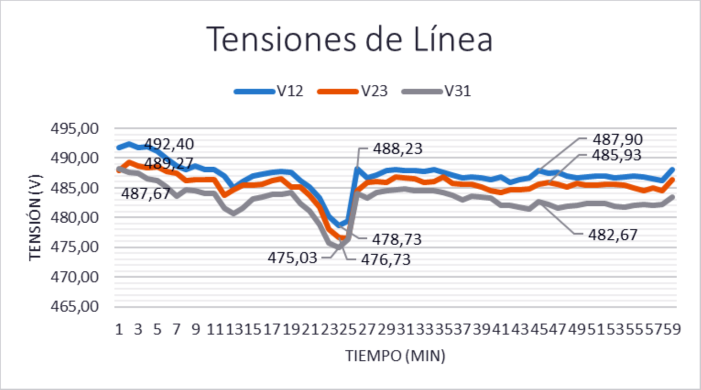

Figure 2. Power lines voltage behavior.

The voltage imbalance (DU): the ratio between the maximum voltage deviation and the average value, is generally expressed as a percentage, and the standards establish a value that does not exceed 5 % for the three-phase asynchronous electric motors. The voltage imbalance obtained of 0.4 5% complies with the standards.

$$Du\,\% = \frac{\max[abs(Uab - Uprom); abs(Ubc - Uprom); abs(Uca) - Uprom]}{Uprom} 100\% \qquad [4]$$

Where:

Uab, Ubc, Uca, Uprom: Voltages between phases a and b, b and c, c and a and average voltage in Volts (V).

Taking into consideration that the nominal voltage of the motors is 460 V, the voltage imbalance with respect to this value and the measured magnitudes, are approximately 6%, so that it is a parameter that does not comply with the standard for the operation of three-phase asynchronous electric motors. The currents for each phase show expected values without large-scale variations (Figure 3).

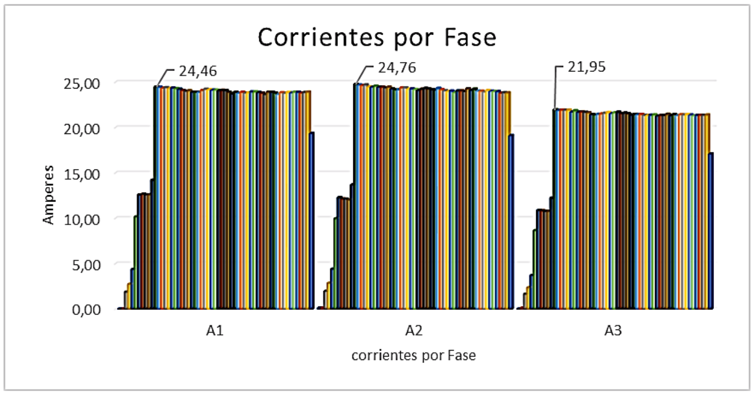

Figure 3. Phased power distribution.

At the pond 45, stocked with specimens, 10 aerators were installed for water oxygenation. Measurements were taken for one hour to monitor the behavior of electrical variables when all the motors were connected. This was the only pond where measurements could be taken with the maximum number of aerators connected, with their protective devices in place, without being affected by the power generation deficit or the lack of electricity. The measuring instrument was installed, and the operation of the installed equipment was verified (Figure 4).

Figure 4. View of the aerator in the pond 45.

The Figure 5 shows the behavior of active, reactive, and apparent power for one hour of measurement. In the first few minutes, it is observed that the power values increase from zero up to reaching a stable maximum power value, maintaining this behavior throughout the measurement period, due to the staggered connection of the 10 motors to avoid the sustained starting current peaks.

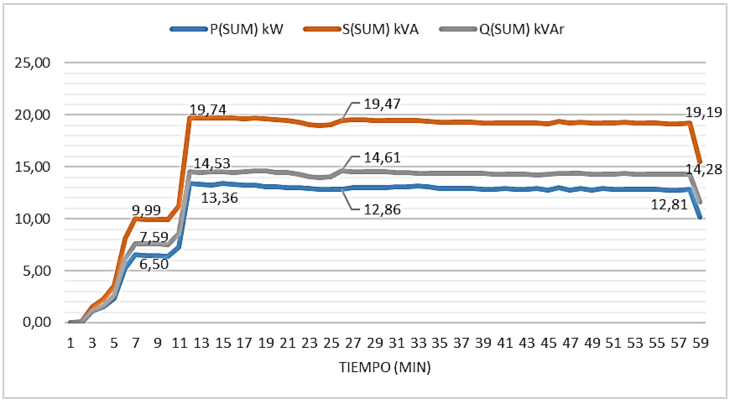

Figure 5. Behavior of active, reactive and apparent power.

At the countertop, half of the motors were connected, with an active power equivalent to 6.5 kW and a reactive power of approximately 7.6 kVAr, with the reactive power being the most prominent at this point. As more load was connected, the reactive power values increased proportionally to the load increase, but their behavior remained consistent, with the higher reactive power values in the network. This resulted in a low power factor (Figure 6). Following the load behavior and connection time, it was observed how the power factor of the induction motors, the main load of Service 4, significantly influenced on the system. The same pattern occurred in Services 1 and 2. Before connecting the motors, the measurement recorded a power factor of approximately 0.42, corresponding to the connection of a 400 W halogen lamp.

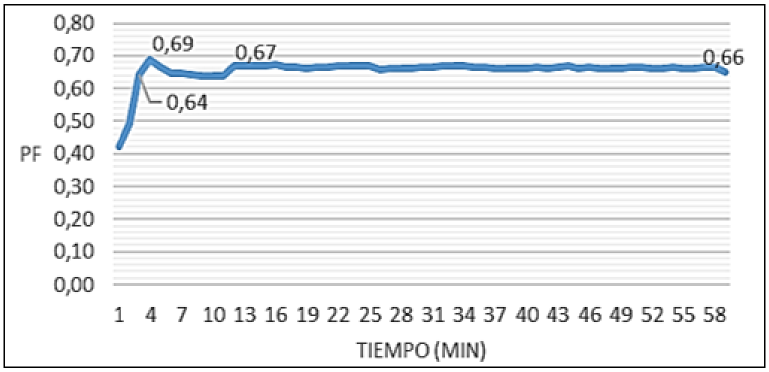

Figure 6. Power factor at the pond 45.

The average power demand of the system when operating at maximum load is 13 kW for an average power factor of 0.66. This indicates that the power factor varies with the load, but since the load is stable over time, fluctuations occur only when the loads are suddenly connected or disconnected. Figure 7 shows the panel operating at normal load and how the active, reactive, and apparent power, as well as the power factor, adapt to the service.

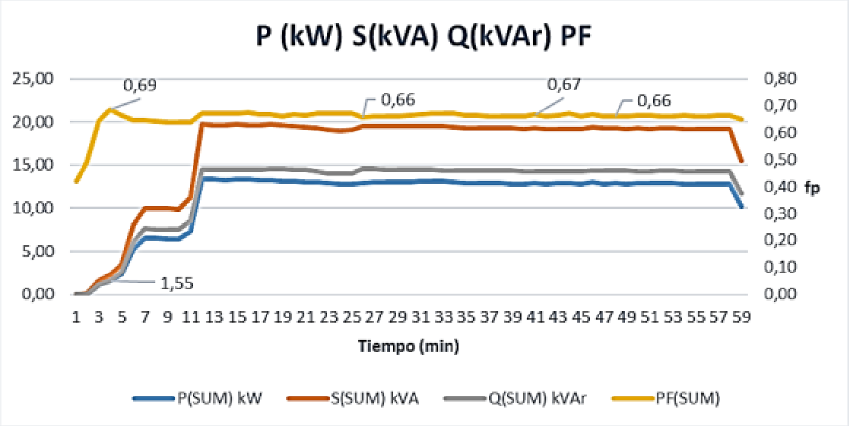

Figure 7. Power ratios and the power factor.

It is verified that the power factor is imposed by the load, which in this case are the induction motors with an average value of 0.66, and its close link with the high and low values of reactive and active power respectively.

3. Analysis of the results

3.1. Pond services based on invoices

The services 1, 2, and 4 supply power to the shrimp ponds, where aerators are used to oxygenate the water. These aerators have a low power factor (between 0.35 and 0.89), resulting in financial penalties. Figure 8 illustrates the power factor performance of services 1, 2, and 4 during 2023.

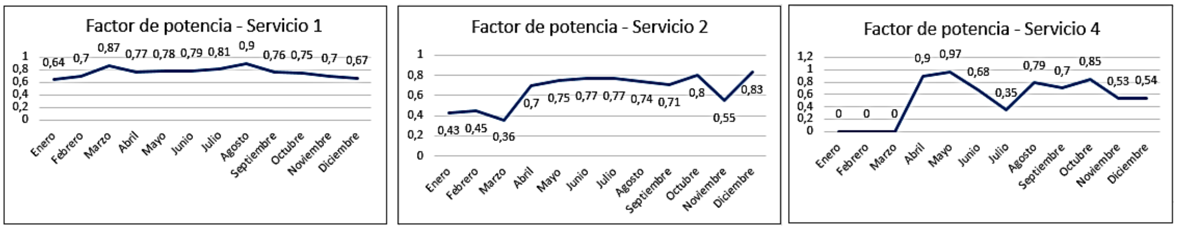

Figure 8. Power factor behavior in services 1, 2 and 4 during 2023.

In the three services there is a variable behavior of this magnitude, for which the final billing for the whole year was higher than the normal billing, as it is shown in the detailed analysis as follows for the services to the ponds.

Service 1:

It has two transformers of 50 and 75 kVA inn incomplete connection, which feed the aerators in ponds 1 to 9. Table 1 shows the behavior of energy consumption, transformation losses and the billing in the months of the year analyzed.

Table 1. Behavior of energy parameters in service 1 (Ponds 1 - 9)

Months	Monthly consumption (kWh)	Transf.Losses (kWh)	Standard billing (CUP)	Power factor	Total billing (CUP)
January	864	444	16297	0,64	22917,66
February	1766	444	18172,69	0,7	23364,8
March	631	401	15376,66	0,87	15906,89
April	11004	466	37997,51	0,77	44412,67
May	14615	648	46849,85	0,78	54057,52
June	14731	482	50054,5	0,79	57024,11
July	1824	430	18600,65	0,81	20667,39
August	444	0	15288,73	0,9	15288,73
September	3137	445	21474,69	0,76	25430,55
October	7813		33700,04	0,75	36987,85
November	6085	452	27124,73	0,7	34874,65
December	7799	444	30388,41	0,67	40820,25
Average	5892,75	423,27	27610,46	0,76	32646,09

The power factor is low and variable between 64 and 87%, primarily due to the aerators, the main load of the service, where the quantity and operation of each pond change considerably. The aerator has a low power factor (65%) (Figure 9).

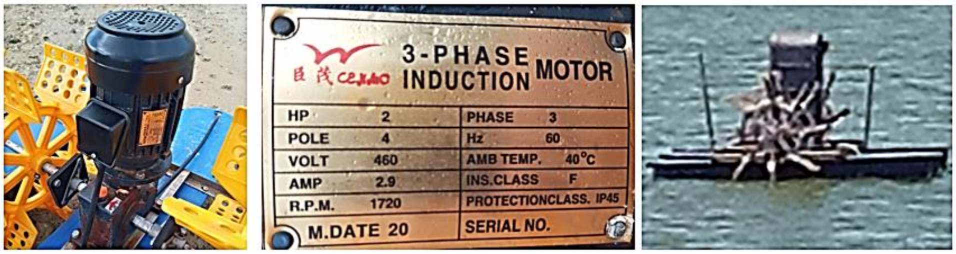

Figure 9. General view of an aerator.

The variation in energy consumption according to the graph is associated with this condition, as well as the conditions of the pond depending on the amount of shrimp to be cultivated and other technological elements in this regard.

Service 2: This corresponds to the power supply for the ponds 10 to 18 and the third block of ponds 19 to 28, provided through a transformer bank (3 x 75 kVA). Table 2 describes the analyzed paratha meters.

Table 2. Behavior in the service 2 of the ponds

Month	Monthly consumption (kWh)	Transf. Losses (kWh)	Standard billing (CUP)	Power Factor	Total billing (CUP)
January	2137	601	15968,56	0,43	33422,57
February	2125	601	15818,58	0,45	31637,16
March	1382	542	13900,26	0,36	34750,65
April	10892	616	34530,39	0,7	44396,22
May	16605	614	48064,81	0,75	57677,77
June	25652	676	73004,55	0,77	85329,99
July	22023	637	64788,82	0,77	75727,19
August	14998	627	45357,52	0,74	55164,55
September	10056	613	33959,56	0,71	43047,33
October	13270		40537,09	0,8	45604,23
November	13765	641	39948,48	0,55	65370,24
December	23021	634	63253,61	0,83	70844,25
Average	12993,83	618,36	40761,02	0,66	53581,01

It has been shown that in the service 2 to the ponds, the power factor is low and varies from 36% to 83%, which is the primary cause of the penalties. In the first three months, with low consumption and power factors below 50%, the company paid more than double the corresponding consumption amount. In the remaining seven months of the year, the company was penalized with percentages between 12% and 63% above the normal billing for the measured energy consumption.

Service 4: It is powered by a transformer bank (3 x 50 kVA), for the rest of the ponds, starting from 29. Table 3 shows the behavior of the parameters analyzed so far.

Table 3. Parameters for service 4 to the ponds from number 29

Months	Monthly consumption (kWh)	Transf. Losses (kWh)	Standard billing (CUP)	Power factor	Total billing (CUP)
January	0	0	0	0	0
February	0	0	0	0	0
March	0	0	0	0	0
April	4472	550	16563,68	0,9	16563,68
May	791	531	9335,86	0,97	8946,86
June	3202	549	18166,81	0,68	24044,31
July	5218	546	22168,65	0,35	57005,1
August	14835	575	41962,49	0,79	47805,37
September	2475	549	13364,18	0,7	17182,52
October	645		9076,15	0,85	10339,92
November	705	548	9156,17	0,53	15548,21
December	2608	532	13405,29	0,54	22342,15
Average	3883,44	547,50	17022,14	0,70	24419,79

There is variation in energy consumption and power factor, August being very high compared to the rest of the year. July saw the lowest power factor value; consequently, the final billing due to penalties was 257% higher than the normal billing for consumption. As can be seen in the billing graph, penalties were applied from May to December.

3.2. Proposed improvements

To address the low power factor, the installation of the capacitor banks is proposed. Additionally, maintenance of the electrical panels and adjustment of motor protection devices are recommended. The presence of power factors between 0.35 and 0.89 in the three associated pond services, compensation of these altered power factors according to the standard, is required.

The method for calculating the Power Factor (cos φ) is the result of applying the cosine φ, which goes with the arc-tangent of the division between the reactive energy (kVArh) and the active energy (kWh), measured over a period of time greater than 24 hours or up to the billing period (Pérez *et al.,* 2022).

$$\text{Power } factor = \cos\left[arctan\left(\frac{kVArh}{kWh}\right)\right] \quad [5]$$

Reactive energy can be produced where it is consumed, through capacitor banks, and it is therefore penalized or rewarded, as follows: Power factor bonuses: Customers who register a power factor greater than 0.92 are rewarded according to the following equation where normal billing does not include penalties and the power factor is the actual one for the period up to a maximum value of 0.96 (Gómez, 2020).

$$Bonus = Standard\ billing\ \left[\frac{0{,}92 - F.Pot.Real}{F.Pot.Real}\right] \quad [6]$$

Power Factor Penalties: If the power factor is less than 0.90, the customer is penalized. The penalty amount is calculated using the following equation, where the normal billing does not include other penalties and the power factor is the actual power factor for the period.

$$Penalizing = Standard\ billing\ \left[\frac{0{,}90 - F.Pot.Real}{F.Pot.Real}\right] \quad [7]$$

- A power factor below 0.90 is penalized.
- Between 0.90 and 0.92, there will not be penalty or bonus.
- A power factor between 0.92 and 0.96 is awarded as a bonus.
- When the power factor is greater than 0.96, the bonus is calculated using the power factor value up to 0.96.

Based on this, the possibility of power factor correction with a capacitor bank for service 4 is analyzed, considering that the average power factor shown in the measurements is 0.66 (Table 4).

Capacity bank power to be installed: Qcap0.95, calculated for a power factor of 0,95:

$$Qcap_{0.95} = Preal(tan\varphi - tan\varphi_{deseado}) = 12{,}97(tan(48{,}4°) - \tan(18{,}19°)) = 10.5\ kVArC \quad [8]$$

Where:
Qcap: Capacitor power
Preal: Real active power of the load.
φ_{real}: Real phase angle
$\varphi_{deseado}$: Desired phase angle

Table 4. Calculation of the capacity to be installed

Denomination	Value	Angle. Grade	Tangent	Q = P(tgφ1-tgφ2) kVArC
Power factor by measurement	0.66	48.36	3.179	
Desired power Factor	0.95	23.074	0.426	10.5 kVArC

This compensation is calculated for a panel of 10 motors (group compensation), which according to the calculation it is standardized to 15 kVArC, but by having 25 panels throughout the cultivation area (each one representing a group) makes it difficult to install compensation by load groups, the panels where they could be installed are far apart from each other, the costs per number of capacitors increase and therefore, a centralized compensation for each of the services in the pond modules is suggested, as it avoids additional costs and the installation, surveillance, monitoring and the maintenance of the equipment is simpler.

For Service 4, with 10 panels, 150 kVArC is required. Consequently, Services 1 and 2 require 75 kVArC and 150 kVArC, respectively.

A LIFASA automatic battery is proposed for centralized power factor correction in low-voltage installations.

4. Discussion

4.1 Electric diagnostic

The diagnosis reveals that services 1, 2, and 4 have a low power factor, resulting in financial penalties. In service 1, the power factor ranged from 0.64 to 0.87, while in service 2 it ranged from 0.36 to 0.83. In service 4, the average power factor was 0.66.

4.2 Power factor correction

The capacity of the capacitor banks was calculated for each service. Service 1 required a 75 kVAr bank, Service 2 a 150 kVAr bank, and Service 4 a 150 kVAr bank. Installing these capacitor banks would increase the power factor to 0.95, eliminating penalties and generating cost savings.

4.3 Environmental-economic impact

Power factor correction results in annual savings of 235,496.05 CUP for pond services. In addition, CO_2 emissions are reduced by 14,305.27 kg annually. Table 5 illustrates the savings achieved. Power factor correction results in annual savings of 235,496.05 CUP for pond services. In addition, CO_2 emissions are reduced by 14,305.27 kg annually. Table 5 illustrates the savings achieved**.**

Table 5. Total savings after connecting the capacitors

Items	Service 1	Service 2	Service 4
Difference between total billing and normal bonus	60427,61	80238,15	66967,84
Total saving	10017,91	13953,06	3891,48
(CUP)	70445,52	94191,21	70859,32

By making an estimated analysis only of the costs of the capacitors, the magnitudes expressed in table 6 can be related.

Table 6. Investment cost and payback period with the proposal

Items	**Service 1**	**Service 2**	**Service 4**
Investment Euro	1603	4178	4178
Investment CUP	41 669.98	108 607.11	108 607.11
Payback	0.59 (7 months)	0.64 (8 months)	1.53 (1 year and 6 months)

Taking into account the values that are shown in tables 5 and 6, regarding the three services to the ponds, savings per year equal to 235496.05 CUP would be obtained**,** which implies a payback period close to two and a half years.

5. Conclusions

The research demonstrates that the reactive power compensation using the capacitor banks is an effective action for improving energy efficiency in the ponds of the Guajaca Frank País Shrimp Farm. The proposed solution does not only reduce economic penalties and increases efficiency by decreasing reactive power, apparent power, and fuel consumption, but also contributes to the environmental sustainability by reducing CO_2 emissions. The results offer the possibility of repetition to improve energy efficiency in similar industrial settings.

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Conflict of Interest: The authors declare that there are no conflicts of interest.

Author's Contribution according to CRediT Taxonomy

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Geidis Jardínez Correa: Investigation/Writing – review & editing